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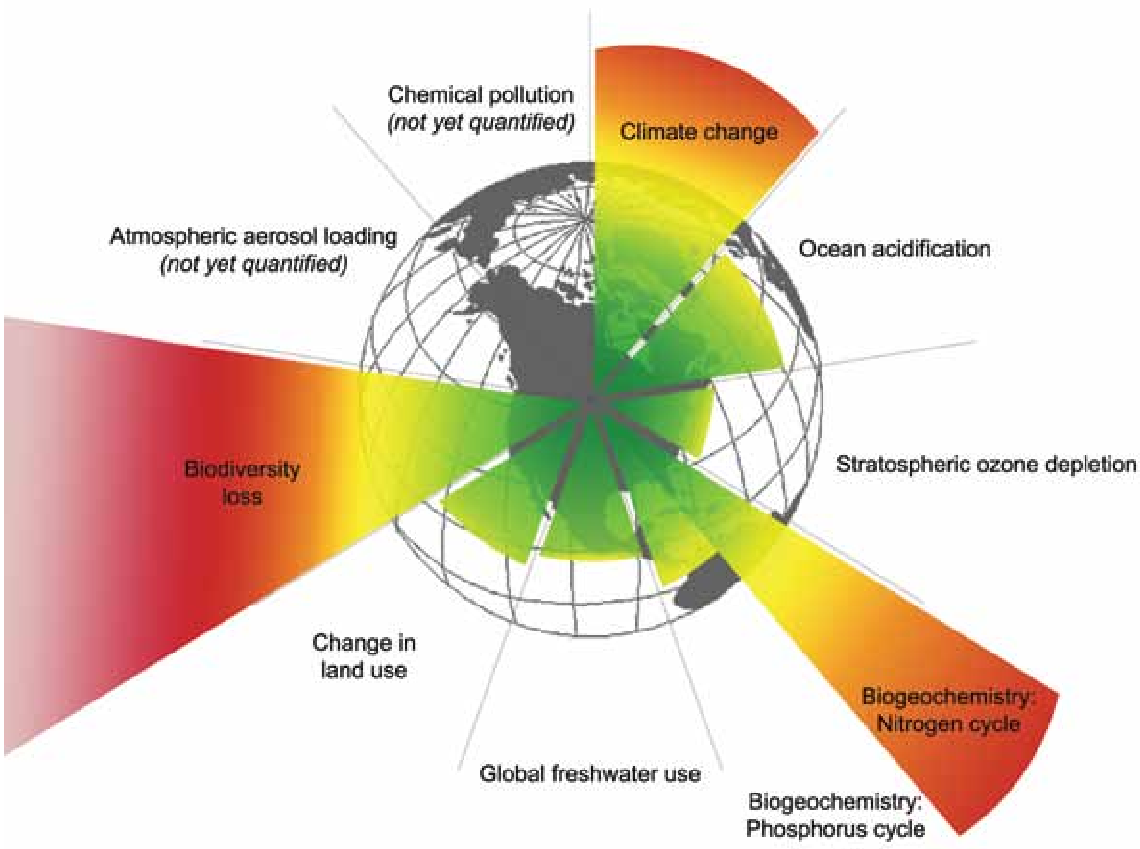
Feature

How Defining Planetary Boundaries Can Transform Our Approach to Growth

by Will Steffen, Johan Rockström, and Robert Costanza



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The globe represents the proposed safe operating space for the nine planetary systems. The wedges represent an estimate of the current position for each variable. The boundaries in three systems (rate of biodiversity loss, climate change, and human interference with the nitrogen cycle) have already been exceeded.

In Brief

Our planet's ability to provide an accommodating environment for humanity is being challenged by our own activities. The environment—our life-support system—is changing rapidly from the stable Holocene state of the last 12,000 years, during which we developed agriculture, villages, cities, and contemporary civilizations, to an unknown future state of significantly different conditions. One way to address this challenge is to determine "safe boundaries" based on fundamental characteristics of our planet and to operate within them. By "boundary," we mean a specific point related to a global-scale environmental process beyond which humanity should not go. Identifying our planet's intrinsic, non-negotiable limits is not easy, but here we specify nine areas that are most in need of well-defined planetary boundaries, and we explain the steps needed to begin defining and living within them.

Author Note: *This article is based on the papers "A safe operating space for humanity,"[1] published in* Nature, *and "Planetary boundaries: Exploring the safe operating space for humanity,"[2] published in* Ecology and Society. *See these papers for a complete description of the planetary boundaries. Here, we present the underlying concepts and suggest ways to limit continued growth of the material economy on a finite planet.*

The Challenge

Over the past half century, we have become adept at dealing with environmental problems on a local and global scale. The worst excesses of the Industrial Revolution have, in many cases, been ameliorated. Rivers, such as the Thames in London, have been cleaned up and the air quality in major cities, such as Los Angeles, is better. Synthetic pesticides once sprayed on our crops, such as DDT, have been banned in most developed countries, and lead has been removed from petroleum-based fuels. These impressive successes have been celebrated, perhaps most notably in Bjorn Lomborg's book *The Skeptical Environmentalist*.[3]

However, to say we have done enough globally would be false on two counts. First, while these problems have been addressed in many European and North American nations, over three-quarters of the world's people do not live in developed countries. For them, many of the local and regional environmental problems still exist and, in many cases, are worsening. Second, the environment—our life-support system—is under increasing threat from a wide range of human pressures, many of them emanating from consumption in the wealthy countries. The deterioration of the global environment puts even more pressure on the poorest countries to limit growth, even as they struggle to bring their populations out of poverty.

This is an entirely new situation for humanity. In the past when we fouled our local environment, we could move to someplace else. As human population has grown, these short-term solutions are no longer viable. Furthermore, the impacts of our presence were not usually felt beyond our immediate surroundings. This is also no longer the case. The global environment has provided an especially accommodating environment over the past 12,000 years for humanity to develop and thrive.[4] But the world population is no longer small, spread out, and technologically limited.

Does our planet have boundaries regarding the amount of growth it can absorb? We believe it does and that certain preconditions must be set that acknowledge and respect those boundaries.

This new situation is captured in the concept of the Anthropocene, a newly defined geological era beginning around the 1800s, with the Industrial Revolution. The term was introduced and popularized by Nobel Laureate Paul Crutzen,[5] who felt the recent influence of human activity on the Earth was significant enough as to constitute the naming of a new epoch. The past 12,000 years or so is a period defined by geologists as the Holocene, an epoch in which global average temperature has been remarkably stable and during which time agriculture developed, followed by the appearance of ever larger settlements and the development of complex civilizations in Africa, Asia, South and Central America, and the Mediterranean region.

Since the Industrial Revolution, the human enterprise has expanded so rapidly that we are now overwhelming the capacity of the Earth system to absorb our wastes and to sustainably provide the services we require. In the period since the Second World War, the acceleration of development has become particularly dramatic. Humanity is fundamentally changing the Earth's physical climate,[6] overwhelming its capacity to provide ecosystem services, homogenizing its biological diversity,[7] and substantially modifying the global cycles of key elements like nitrogen, carbon, and phosphorus.[8] We are indeed passing through the exit door of the Holocene and into the unknown world of the Anthropocene.

So what is the solution to this dilemma? Humanity needs to change course, but in what direction and what principles should guide the journey? The problem has been recognized for several decades, and many attempts have been undertaken to define or inform solutions—limits to growth,[9] safe minimum standards,[10] the precautionary approach,[11]

Key Concepts

- **In the last 200 years, humanity has transitioned into a new geological era—termed the Anthropocene—which is defined by an accelerating departure from the stable environmental conditions of the past 12,000 years into a new, unknown state of Earth.**
- **In order to maintain a global environment that is conducive for human development and well-being, we must define and respect planetary boundaries that delineate a "safe operating space" for humanity. We must return to the long-term stable global environment that nurtured human development.**
- **The nine areas that are most in need of planetary boundaries are climate change, biodiversity loss, excess nitrogen and phosphorus production, stratospheric ozone depletion, ocean acidification, global consumption of freshwater, change in land use for agriculture, air pollution, and chemical pollution.**
- **We estimate that humanity has already transgressed three of these boundaries: climate change, biodiversity loss, and phosphorus production.**
- **Several steps can be taken to establish and enforce these boundaries, and they are suggested here.**

and tolerable windows,[12] for example. These provide an excellent knowledge base from which to work toward a more sustainable future.

The Concept of Planetary Boundaries

How do we begin to identify what aspects of our planet need boundaries and what those boundaries are? The concept of planetary boundaries,[1,2] while building on earlier efforts, takes a rather different approach. It does not focus so directly on the human enterprise, as do most of these earlier approaches, but rather emphasizes the Earth as a complex system. Here we identify nine areas that are most in need of set planetary boundaries: climate change; biodiversity loss; excess nitrogen and phosphorus production, which pollutes our soils and waters; stratospheric ozone depletion; ocean acidification; global consumption of freshwater; change in land use for agriculture; air pollution; and chemical pollution (*table 1*).

What do we mean by "boundary"? This refers to a specific point related to a global-scale environmental process beyond which humanity should not go. The position of the boundary is a normative judgment, informed by science but largely based on human perceptions of risk. This doesn't mean that any change in the Earth system is dangerous. Our planet can undergo abrupt changes naturally. An example is the sudden switch in North Atlantic ocean circulation when a critical level of freshwater input is reached. But these thresholds and abrupt changes are intrinsic features of the Earth system and cannot be eliminated or modified by human actions, such as the development of new technologies. We have to learn to live with thresholds and respect them. An abrupt change is a hardwired feature of the Earth system independent of human existence, while violation of a boundary is a subjective judgment by humanity about how close we wish

Table 1: Categories of Boundaries

BOUNDARY CHARACTER / SCALE OF PROCESS	PROCESSES WITH GLOBAL SCALE THRESHOLDS	SLOW PROCESSES WITHOUT KNOWN GLOBAL SCALE THRESHOLDS
SYSTEMIC PROCESSES AT PLANETARY SCALE	CLIMATE CHANGE	
	OCEAN ACIDIFICATION	
		STRATOSPHERIC OZONE
AGGREGATED PROCESSES FROM LOCAL/REGIONAL SCALE		GLOBAL P and N CYCLES
		ATMOSPHERIC AEROSOL LOADING
		FRESHWATER USE
		LAND-USE CHANGE
		BIODIVERSITY LOSS
		CHEMICAL POLLUTION

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Our initial analysis yielded nine planetary boundaries for Earth-system processes, such as for climate change, which undoubtedly features threshold/abrupt change behavior, and for others, such as biodiversity loss, which are slow processes that erode resilience over time.

to approach dangerous or potentially catastrophic thresholds in our own life-support system.

Climate change, biodiversity loss, and phosphorus and nitrogen production are just three areas in which boundaries can be determined and measured, and we will use these as examples.

Human-provoked climate change is no longer disputed. Scientists can measure climate change by studying the levels of CO_2 in our atmosphere. Our proposed climate boundary is that human changes to atmospheric CO_2 should not drive its concentration beyond 350 parts per million by volume, and that radiative forcing—the change in the energy balance at the Earth's surface—should not exceed 1 watt per square meter above preindustrial levels. Transgressing these boundaries could lead to the melting of ice sheets, rising sea level, abrupt shifts in forest and agricultural land, and increasing intensity and frequency of extreme events like floods, wildfires, and heat waves.

A second example is biodiversity loss, which does occur naturally and would continue to some degree without human interference. However, the rate of animal extinction has skyrocketed in the postindustrial age. Compared with fossil records, today the rate of extinction per species is 100–1,000 times more than what could be considered natural. Human activities are to blame: urban and agricultural development, sprawl, increases in wildfires that destroy habitat, introduction of new species into environments, and the exploitation of land for human consumption—such as the destruction of the rainforests. We believe another 30 percent of wildlife will come under the threat of extinction this century if change is not made. The dangers of biodiversity loss go beyond nostalgia for certain animals: entire ecosystems rely on certain threatened species.

Setting a planetary boundary for biodiversity is difficult because there is so little known about the way in which species are interwoven and how they connect to the broader environment. However, we propose beginning by using the extinction rate as a flawed but acceptable indicator. Our suggested planetary boundary is that of ten times the background rate of extinction. More research may change this boundary.

In our third example, we propose that no more than 11 million tonnes of phosphorous should be allowed to flow into the ocean each year—which is ten times the natural background state. Excessive production of phosphorus, along with nitrogen, is a by-product of our agricultural system. Excessive phosphorous and nitrogen production pollutes waterways and coastal areas and adds harmful gases to the atmosphere. Current levels already exceed critical thresholds for many estuaries and freshwater sites, and so further research may reduce the current phosphorus and nitrogen boundaries.

We propose that a boundary be set for each of the nine areas and that it be respected globally, in order for humans to continue along a healthy, productive path for an indefinite amount of time (*table 2*). It is important to acknowledge that we don't know precisely where the threshold might lie along the control variable (i.e., a variable—sometimes a human intervention—that can influence whether or not a threshold is crossed) or how much change in a slow process will undermine resilience at larger scales. Thus, we need to define a zone within which we are reasonably sure the threshold lies or beyond which we are reasonably sure that a significant degree of resilience will be lost.

Staying within the "planetary playing field" does not assure that humanity will thrive, or even survive, but straying outside the playing field will make it very difficult for humanity to thrive under any circumstances. Implementing the concept of planetary boundaries presents huge challenges for global governance and institutions.

Critical Features of the Planetary Boundaries Concept

Several features of the planetary boundaries conceptual framework are critical to understanding how the approach works.

First, planetary boundaries are explicitly designed for the global scale and are aimed at keeping the Earth within safe ranges that existed prior to the Industrial Revolution. Although some Earth-system processes, such as ocean acidification, are intrinsically global in scale, others become global only when they aggregate from much smaller scales.

In no way does this mean that local or regional environmental issues, which have largely been the focus of policy and management for decades, have become less important. Efforts to reduce pollution and limit and reverse ecosystem degradation at local and regional scales continue to be very important and in fact have become even more important because of their larger-scale implications. However, we must now also focus on the global scale explicitly—in addition to and not at the expense of the many environmental issues we still need to solve at smaller scales. A global solution to the sustainability challenge is thus a prerequisite for living sustainably at local and regional scales.

Second, there is much interaction among the planet's features that lies at the heart of the planetary boundaries approach. This is not at all surprising given that the Earth behaves as a single, complex system at the global scale, but it does complicate the formulation and implementation of planetary boundaries. There are cascading impacts, in which transgressing one boundary can have implications for other boundaries. For example, converting the Amazon rainforest to a grassland or savanna could influence atmospheric circulation globally and ultimately affect water resources in East Asia through changes in rainfall.

Even small changes can have a synergistic effect when linked to other small changes. For example, conversion of forest to cropland, increased use of nitrogen and phosphorus fertilizers, and increased extraction of freshwater for irrigation could all act together to reduce biodiversity more than if each of these variables acted independently. Many changes feed back into each other. The processes involving ocean acidity and atmospheric CO_2 concentration are an example of a reinforcing feedback loop. An increase in ocean acidity reduces the strength of the "biological pump" that removes carbon from the atmosphere, which in turn increases the atmospheric CO_2 concentration, which increases the physical uptake of CO_2 by the ocean, which further increases acidity, and so on.

Finally, the planetary boundaries approach doesn't say anything explicit about resource use, affluence, or human population size. These are part of the trade-offs that allow humanity to continue to pursue increased well-being. The boundaries simply define the regions of global environment space that, if human activities push the Earth system into that space, would lead to unacceptably deleterious consequences for humanity as a whole.

Because the planetary boundaries approach says nothing about the distribution of affluence and technologies among the human population, a "fortress world," in which there are huge differences in the distribution of wealth, and a much more egalitarian world, with more equitable socioeconomic systems, could equally well satisfy the boundary conditions. These two socioeconomic states, however, would deliver vastly different outcomes for human well-being. Thus, remaining within the planetary boundaries is a necessary—but not sufficient—condition for a bright future for humanity.

Table 2: Planetary Boundaries

Earth-System Process	Parameters	Proposed Boundary	Current Status	Pre-industrial Value
Climate Change	**(i) Atmospheric carbon dioxide concentration** (parts per million by volume) **(ii) Change in radiative forcing** (watts per meter squared)	350 1	387 1.5	280 0
Rate of Biodiversity Loss	**Extinction Rate** (number of species per million species per year)	10	>100	0.1-1
Nitrogen Cycle (part of a boundary with the phosphorus cycle)	**Amount of N_2 removed from the atmosphere for human use** (million of tonnes per year)	35	121	0
Phosphorus Cycle (part of a boundary with the nitrogen cycle)	**Quality of P flowing into the oceans** (million of tonnes per year)	11	8.5-9.5	-1
Stratospheric Ozone Depletion	**Concentration of ozone** (Dobson unit)	276	283	290
Ocean Acidification	Global mean saturation state of aragonite in surface sea water	2.75	2.90	3.44
Global Freshwater Use	**Consumption of freshwater by humans** (km^3 per year)	4,000	2,600	415
Change in Land Use	Percentage of global land cover converted to cropland	15	11.7	Low
Atmospheric aerosol loading	Overall particulate concentration in the atmosphere, on a regional basis	To be determined		
Chemical Pollution	For example, amount emitted to, or concentration of persistent organic pollutants, plastics, endocrine disrupters, heavy metals, and nuclear waste in, the global environment or the effects on the ecosystem and functioning of Earth system thereof	To be determined		

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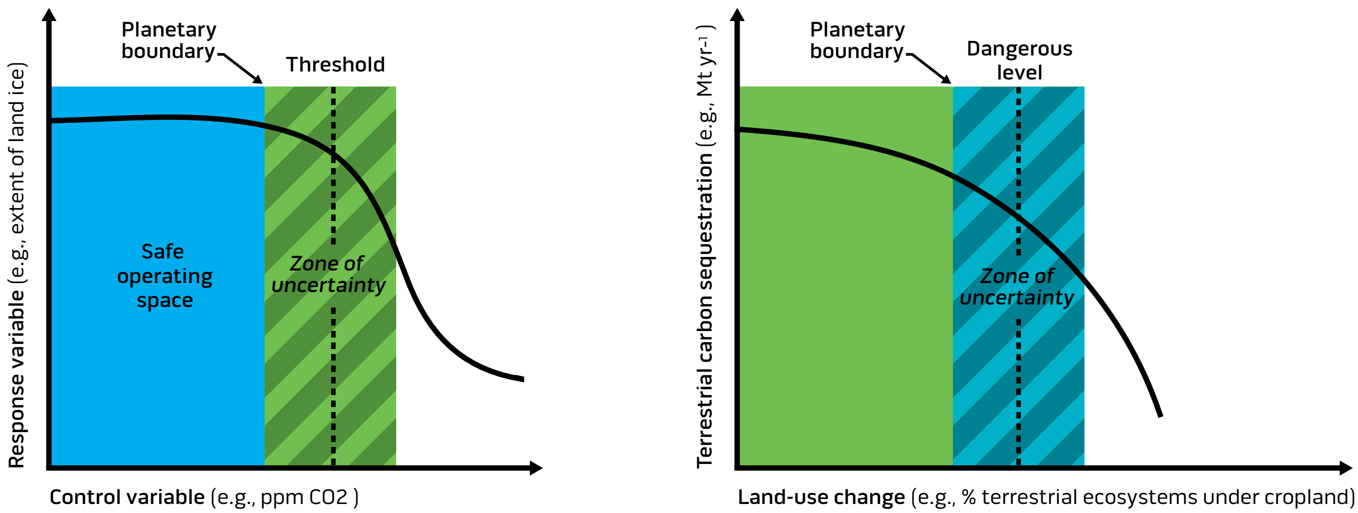
We have assigned a control variable (or parameter) to each of the Earth-system processes and, in addition, have taken a first guess—some better substantiated than others—at a planetary boundary for each. To see how humanity is faring with respect to the boundaries, we have listed the current and preindustrial values of the control variable along with the proposed boundary.

Conceptual Diagram of Boundary, Threshold, and Zone of Uncertainty



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The left panel shows a boundary for a process that has a well-defined threshold, leading to an abrupt change if that threshold is crossed. The right panel shows a boundary for a "slow" process that does not have a threshold but is important for maintaining resilience at regional or global scales. In each case there is a zone of uncertainty as to where the threshold lies or where an unacceptable erosion of resilience occurs.

The Implications for Governance

As a practical solution for living sustainably in the modern era, the planetary boundaries approach raises important questions and opportunities for governance and institutions, even to the point of challenging the concept of national sovereignty. We have identified four specific challenges for governance:[13]

- *Early-warning systems.* The nature of Earth-system dynamics—the nonlinearities, tipping elements, thresholds/abrupt changes—strongly suggests that humanity needs a system to warn us when we are approaching such potentially catastrophic points. Indeed, the planetary boundaries approach is based directly on this feature of the Earth system. An early-warning system is a prerequisite for being able to recognize and steer away from such thresholds.
- *Dealing with uncertainties.* Each of the planetary boundaries is placed within a zone of uncertainty, some much larger than others. Although further scientific research will reduce these uncertainties in many cases, they will never be completely eliminated. In a poisonous political environment, uncertainties can be exploited as reasons for inaction, but scientists must be able to address uncertainty without being attacked. A global governance system will need to live with a certain level of uncertainty, emphasizing the need for a precautionary approach when determining the position of boundaries.
- *Multilevel governance.* Interacting with the traditional institutions that currently exist at national, subnational, and local levels will be necessary, and probably will be complex and challenging to implement. Creating effective multilevel governance systems will be especially important for those planetary boundaries that are based on aggregates of many local and regional actions.
- *Capacity to assimilate new information.* In addition to reducing the zone of uncertainty for some boundaries, scientific research will continue to uncover more insights into the dynamics of the Earth system itself. This could lead to the need for additional planetary boundaries or the reformulation of existing ones. The increasing flow of new scientific information will undoubtedly put pressure on any institutional framework to keep up with the pace of new knowledge. A case in point is in the debate over how much greenhouse gas can be released without disastrous effects. After a long time trying to convince the international community that the climate change boundary should be 450 ppm CO_2, a growing number of scientists are suggesting that a 350 ppm CO_2 boundary would be more appropriate.

Ultimately, there will need to be an institution (or institutions) operating, with authority, above the level of individual countries to ensure that the planetary boundaries are respected. In effect, such an institution, acting on behalf of humanity as a whole, would be the ultimate arbiter of the myriad trade-offs that need to be managed as nations and groups of people jockey for economic and social advantage. It would, in essence, become the global referee on the planetary playing field. While humanity is still a long way from meeting this challenge, some creative thinking about new institutions is showing some promise. For example, one proposed institution that moves in this direction is the Earth Atmospheric Trust,[14] which would treat the atmosphere as a global common property asset managed as a trust for the benefit of current and future generations.

Summary and Conclusions

Earth-system science is still in its infancy and much more needs to be known to create a robust solution to humanity's global dilemma. Nevertheless, we know enough now about the functioning of the Earth system that we must learn to respect the hardwired limits of our own life-support system. And we must find practical ways to respect those limits. Much more work is required to refine the concept of planetary boundaries and make it operational. The nine proposed boundaries outlined here are a preliminary estimate. For some of the boundaries, the zone of uncertainty is still huge, and for two of them—atmospheric aerosol loading and chemical pollution—we are unable to make even a first, rough guess at where the boundary might lie. In fact, we are not even sure that these nine boundaries are sufficient to define the planetary playing field; more may be needed.

Just when we are now developing some solutions for environmental problems at the local and regional scales—at least in developed countries—we are confronting the challenge of a more complex nature at the global scale. Climate change is just the tip of the proverbial iceberg, with many more linked environmental and socioeconomic and cultural changes sweeping rapidly across the planet.

Effective solutions for living sustainably in the postindustrial age require innovative frameworks and implementation strategies. Rather than tackling these global-scale problems one by one, as we are attempting for climate change, we need a far more holistic and integrated approach. The planetary boundaries framework provides such an approach.

Within the boundaries of the planetary playing field, there is an infinite number of strategies, tactics, and trade-offs that humanity can deploy as it continues to strive to improve well-being. The rules of the game are familiar—economics, trade, laws and regulation, ethics, local and regional environmental protection, and so on. What is new is that the playing field for this game is not infinite; it has boundaries and the players must respect these boundaries.

Implementing the concept of planetary boundaries presents huge challenges for global governance and institutions. Science is on the way to defining the planetary playing field, but we have yet to define the roles of the global referees and grant them the authority to keep the players on the field.

Respecting the boundaries means respecting the global commons—the atmosphere, oceans, and ecosystem functioning and the services derived from that functioning. The solution, as Peter Barnes[15] has suggested, is to greatly expand the "commons sector" of the global economy with institutions that can keep humanity within a safe operating space. These new kinds of commons institutions need to be developed at multiple scales, from local to global, with participation of the affected stakeholders.[16] *Solutions* will provide a venue for this critical ongoing discussion and design process.

References

1. Rockström, J et al. A safe operating space for humanity. *Nature* 461, 472–475 (2009).
2. Rockström, J et al. Planetary boundaries: Exploring the safe operating space for humanity. *Ecology and Society* [online] 14, 32 (2009). www.ecologyandsociety.org/vol14/iss2/art32.
3. Lomborg, B. *The Skeptical Environmentalist: Measuring the Real State of the World* (Cambridge University Press, Cambridge, UK, 2001).
4. Costanza, R et al. Sustainability or collapse: What can we learn from integrating the history of humans and the rest of nature? *Ambio* 36, 522–527 (2007).
5. Crutzen, P. The effects of industrial and agricultural practices on atmospheric chemistry and climate during the Anthropocene. *Journal of Environmental Science and Health* 37, 423–424 (2002).
6. International Panel on Climate Change (IPCC) in *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Solomon, S et al., eds), Climate change 2007: The physical science basis (Cambridge University Press, Cambridge, UK, 2007).
7. Millennium Ecosystem Assessment (MEA). *Ecosystems and Human Well-Being: Synthesis* (Island Press, Washington, DC, 2005).
8. Steffen, W et al. *Global Change and the Earth System: A Planet under Pressure* (Springer Verlag, Heidelberg, Germany, 2004).
9. Meadows, DH, Meadows, DL, Randers, J & Behrens, WW. *The Limits to Growth* (Universe Books, New York, 1972).
10. Ciriacy-Wantrup, SV. *Resource Conservation: Economics and Policies* (University of California Press, Berkeley, 1952).
11. Raffensperger, C & Tickner, W, eds. *Protecting Public Health and the Environment: Implementing the Precautionary Principle* (Island Press, Washington, DC, 1999).
12. German Advisory Council on Global Change (WBGU). *Scenario for the Derivation of Global CO2 Reduction Targets and Implementation Strategies: Statement on the Occasion of the First Conference of the Parties to the Framework Convention on Climate Change in Berlin* (March 1995) [online]. www.wbgu_sn1995_engl.pdf.
13. Young, OR & Steffen, W in *Principles of Ecosystem Stewardship: Resilience-Based Natural Resource Management in a Changing World* (Chapin, FS, Kofinas, GP & Folke, C, eds), The Earth system: Sustaining planetary life-support systems, 295–315 (Springer, New York, 2009).
14. Barnes, P et al. Creating an earth atmospheric trust. *Science.* 319, 724 (2008).
15. Barnes, P. *Capitalism 3.0: A Guide to Reclaiming the Commons* (Berrett-Koehler, San Francisco, 2006).
16. Ostrom, E. 2010. A multiscale approach to coping with climate change and other collective action problems. *Solutions* [online] 1, 27–36. www.thesolutionsjournal.com/node/565.